

QUANTIFICATION OF CONTAMINANTS  
ASSOCIATED WITH LDEF\*

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## SUMMARY

The standard particle size distribution curves of MIL STD 1246B are not representative of particle distributions found on LDEF. The distribution follows a log/log squared plot but there are far fewer small particles than would be predicted by the standard curve based on the population of larger particles. By changing the slope of the distribution curve to about 0.40 rather than the standard curve slope of 0.93 the LDEF particle distribution is better represented. Using a slope of 0.40 and labeling the curve by its intercept with the abscissa value of 1 the cleanliness of LDEF is approximately a level 5000. This new curve intercepts the standard Level 1000 curve at about 250 micrometers and a Level 500 curve at about 50 micrometers. The results of forty-four separate surface particle counts are presented in this paper. They represent counts made directly from LDEF surfaces as well as the results from tapelifts taken from LDEF or associated surfaces. Consecutive tapelift samples collected from the exact same locations in the Shuttle Bay before and after various operations were used to monitor the redistribution of particles during those events. Based on these studies a significant redistribution of particulate matter occurred during the reentry and during the ferry flights. Airborne particle counts and particle fallout monitoring in the SAEF-2 clean room appear to underestimate the particulate contaminant impact on surfaces in SAEF-2. Tapelift samples of surfaces in SAEF-2 suggest particle fallout rates of non-LDEF materials near LDEF much higher than those predicted by the particle fallout monitoring samples. The airborne particle counts in SAEF-2 indicated a well controlled environment though pollen grains and other natural airborne particles from exterior environments were found distributed over the surface of LDEF.

When LDEF was first seen close-up in orbit a brown molecular film was evident over much of its surface. The amount of molecular film deposited or fixed in place on the surface of LDEF while it was in orbit is estimated at approximately one pound. This represents approximately 10 to 15% of the material outgassed from paints, silicones, and other materials present on or in the experiment trays. The amount of non-volatile residue (NVR) on LDEF when it entered orbit was approximately 2.5 milligrams per square foot (MIL STD Level C) based on analyses of the remaining residues found under tray clamps. If all of this film had been converted to a fixed film in orbit it would have represented less than 10% of the estimated amount of molecular film found on LDEF after recovery.

## INTRODUCTION

This paper addresses the quantification of contaminants on the LDEF satellite and associated hardware or tools. The purpose of this study was to provide a background database for the evaluation of the surface of LDEF and the effects of orbital exposure on that surface. This study necessarily discusses the change in the distribution of contaminants on LDEF with time and environmental exposure. Much of this information may be of value for the improvement of contamination control procedures during ground base

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operations. The particulate data represents the results of NASA contractor monitoring as well as the results of samples collected and analyzed by the authors. The data from the tapelifts collected in the Shuttle Bay at Edwards and at Kennedy are also presented. The amount of molecular film distributed over the surface of LDEF is estimated based on measurements made at specific locations and extrapolated over the surface area of LDEF. Some consideration of the total amount of volatile-condensable materials available to form the resultant deposit is also presented. All assumptions underlying these estimates are presented along with the rationale for the conclusions. Each section of this paper will be presented in a subsection for particles and another for molecular films.

### Method for the Quantification of Particulate Contaminants

Tapelifts of particles were collected from some LDEF surfaces directly as well as from associated hardware; the Shuttle Bay, the Transportation Canister, LDEF Active Transport System (LATS), etc. Numbered kits, each containing specially prepared and numbered microscope slides and a roll of lifting tape, were provided to NASA investigators, principal investigators, and other interested parties. The tapelifts collected by the authors and those returned to us by others for analysis were then processed to facilitate both qualitative and quantitative analysis. The tape used to collect the particles was 3M "Magic™ Tape" with the acrylic adhesive. This tape was used because the plastic film can be dissolved with acetone leaving the particles behind in a thin layer of adhesive. The adhesive has a refractive index of approximately 1.49. This particle containing film was then mounted in a synthetic resin with a refractive index of 1.515. The quantitative analysis was performed using an Olympus Corporation "Cue" system automated image analyzer and transmitted darkfield illumination. One square inch of tape surface was analyzed which corresponded to one to four square inches of surface area depending on the number of times the tape had been applied to the surface; multiple lifts with a single piece of tape were often made to improve the statistical basis of the analysis. The size of each particle was taken as its greatest dimension in accordance with MIL STD 1246B. The Cue image analysis system was configured with a pixel dimension of 5.5 micrometers (video resolution limit) using an objective with a resolution limit of about 4 micrometers ( $NA = 0.1$ ). Transmitted darkfield illumination tends to cause particles to look larger than they are by creating a halo of light around the particle. The halo effect is significant for particle images on the same order of magnitude as the pixel dimension but becomes a small positive bias for larger particles. This bias was reduced by electronically removing the outermost edge of detected particles (the one pixel wide halo around the particles) prior to analysis. Darkfield illumination was used because it produces a bright ring of light around the edge of all particles, transparent or opaque, with the interior being bright for transparent particles and dark for opaque particles (see Photograph 1). By electronically filling in the ring and then removing the halo the particles were more accurately imaged for analysis.

The quantification of particles directly from LDEF surface materials was performed in a Class 100 clean room using an Olympus BH-2 microscope on a boom stand, or a Nikon Optiphot for smaller objects, both with episcopic darkfield and oblique top-light illumination. These counts were performed manually. A few of these counts were further subdivided into those particles present at the time LDEF entered orbit, those that remained fixed in position during reentry and the ferry flight, and those that were present on the surface at the time of analysis that were new or that were not in a position they had occupied while in orbit. These detailed counts were made on the assumption that spot shadows indicated the presence of particles during orbit, particles with shadows beneath them of a similar shape had remained in position since orbit insertion, and particles not associated with such a shadow had moved or been added to the surface during recovery or later (see Ref. 1). These manual counts often involved relatively small areas of the surface and frequently areas very near a tray edge. No single analysis of contaminants on the surface of LDEF can be considered characteristic of the total surface of LDEF but rather of a specific type of micro-environment (Ref. 2). The tray edge constituted one such environment, the center of flat ridged panels another, the longeron surfaces another, etc. The significance of each microenvironment in terms of the dynamics of contaminants is still being evaluated but the combined data provides a good indication of the range of variation in surface cleanliness of LDEF and of the relative cleanliness by specific location. Many areas of

specific interest have not been available for analysis but similar surfaces or a study of the range of values from different surfaces should be useful for extrapolation to specific cases.

The results of the quantitative analyses were plotted on a log/log graph along with a chart of MIL STD 1246B (see Figures 1 through 3, 5, and 6). The counts made manually begin at particles fifty micrometers or greater in length. Those made using image analysis begin at twenty-five micrometers though the value of total detected particles, including those below twenty-five micrometers, is plotted beginning at the one micrometer position on the graph. Figure 4 illustrates the particle fallout rate reported for the SAEF-2 facility and the LATS during the time between LDEF arrival in SAEF-2 and the end of LDEF related activities in SAEF-2. These counts are based on the particles that were collected on a forty-seven millimeter membrane filter over a specific time interval. In SAEF-2 this interval was generally fourteen days. The values for the Transportation Canister (Jan 30 - Feb 1) are based on a two day interval and those for the transport of LDEF to SAEF-2 on the LATS (Feb 1 to Feb 6) are for a five day interval. Figure 7 illustrates the hourly airborne particle count as determined by an automated particle counter for the SAEF-2 Airlock and the SAEF-2 Highbay from the arrival of LDEF in SAEF-2 until the removal of the last tray. The data for Figures 4 and 7 was provided by NASA.

### Methods for the Quantification of Molecular Films

Brown molecular films were widely dispersed over the surface of LDEF. Some of these films were quantified by direct measurement of their cross-section. These thicker films occurred at vent surfaces facing the ram direction primarily on the earth and space ends of LDEF but also along the edges of longerons and tray edges with that orientation. In many areas these films were peeling or curling away from the surface. The curling was always convex to the surface of LDEF as a result of stresses accumulated over the thickness of the film. Attempts to flatten the film caused it to break. Samples of these films were collected and cross-sectioned or optically sectioned to determine their thickness. Optical sectioning is done by carefully focusing on the top of the film and then focusing through the film to its lower surface. The distance moved between the two focal planes times the refractive index of the film is the thickness of the film.

Another technique used is based on the thin film interference colors such as those seen in oil films on water. The sequence of colors seen is a direct measure of optical thickness which can be converted to actual thickness by multiplying the optical thickness by the refractive index of the film. The color effects are due to destructive and constructive interference between the light reflected from the top of the film and that reflected by the back surface. Film thicknesses of one quarter of a wavelength result in destructive interference for that wavelength or color with the result that its complimentary color is seen. Differences of half a wavelength create constructive interference and enhance the brightness of that color. These effects produce characteristic colors over a range of from about 50 nanometers to about 2000 nanometers for the films on LDEF. The interference technique is illustrated on the left side of Figure 8. Figure 8 also provides the film thickness that corresponds to specific colors or sequences of colors based on the measured refractive index of the film, 1.58. Photograph 2 illustrates the interference colors seen on white paint (A276) on a corner bracket of tray H-06.

These two techniques were adequate for very thick films, those over about 20 micrometers, that could be peeled, or those between 0.1 to 2.0 micrometers that generated quantifiable interference colors or sequences of colors. Thinner films could be detected by very slight discoloration but could not be quantified reliably. Films on anodized aluminum didn't produce reliable interference colors due to the effects of the anodized film thickness and irregular surface and the optical complexity of the interface between the aluminum oxide film of the anodize coating and the molecular film. Films between 2.0 and 20 micrometers were semiquantified by their color saturation (brown intensity). Black or browns that were unusually dark could not be semi-quantified in this manner because these films had a stronger absorption coefficient and a broader absorption spectrum than was typical in most of the films. Additional films or

surface alterations of materials were detected by ultraviolet light (see Ref. 3, photograph 4). Some films could only be detected by ultraviolet light or by infrared analysis, having no visible light image. These films are noted but no attempt has been made to quantify them at this time. Some of these fluorescing films are known to be the result of surface chemical modifications and not depositions of molecular contaminants.

Evidence used to estimate the amount of pre-launch non-volatile residue (NVR) was of three main types. The first was the analysis of residues found under clamps, on shims, and on other 'protected' surfaces of LDEF to determine the amount and nature of the deposits after nearly six years in orbit. The second involved estimates based on evaporitic rings around bolts or fixtures (Ref. 3, photograph 3), distribution of fingerprints (Photograph 3), and 'drip' marks on the surface of panels in trays on LDEF. The third was based on the tendency for unpainted anodized aluminum surfaces to collect hydrocarbons. No direct tests for surface cleanliness, particulate or NVR, had been performed prior to the launch of LDEF. Material inventories, the direct measurement of paint film thicknesses, and the weights of silicone materials collected from some trays were used to estimate the amount of volatiles and volatile/condensable materials available on LDEF.

### Results for the Quantification of Particles

The particle distribution curves representative of LDEF surfaces do not relate well to the cleanliness standard curves of MIL STD 1246B (Ref. 4). The MIL STD 1246B graph of the log of particle population (abscissa) by the log squared of the particle diameter (ordinate) with a slope of 0.93 is reasonable for a freshly cleaned surface (Ref. 6) but, as has been reported elsewhere (Ref. 5), the slope of 0.93 used on the standard curves is much too steep for the accumulated debris seen on surfaces exposed to particle fallout. The actual particle distribution on LDEF follows a log/log squared distribution and can be well described by its slope on the graph and by the value on the ordinate of its intercept with the abscissa value of 1. This is the most convenient method of identifying a particle distribution curve and is the method used to identify the curves used in MIL STD 1246B. The last chart in Figure 3 presents the standard curves for MIL STD 1246B Level 500 and Level 1000 and the curves with a slope of 0.38 for level 500, 1000, and 5000, the numerical designation in each case indicating the ordinate value when the abscissa value is 1. Trying to describe a particle size distribution with a slope other than 0.93 in terms of the 0.93 curves becomes a listing of the intercepts of the actual distribution curve with standard curves of various "cleanliness" designations. For example, a surface with a particle distribution having a slope of 0.38 and an ordinate value of 5000 when the abscissa is 1 can be said to meet a MIL STD 1246B Level 1000 for particles less than 250 micrometers in diameter and a Level 500 for particles less than 50 micrometers in diameter. Its actual "cleanliness" becomes rather arbitrary, dependent upon the particle size considered "relevant". The set of curves on the last graph of Figure 3 will be referenced when discussing the cleanliness level of LDEF surfaces. Notice that when the log/log squared curves of MIL STD 1246B are plotted on log/log charts, as in Figure 3, the curves are concave downward. This pattern was typical of nearly all of the tapelift and surface count data.

The earliest particle samples of an LDEF associated surface were those collected from the Shuttle Bay at Edwards. Nine tapelifts were collected in the bay at Edwards. The first three were collected shortly after landing but only the first two were recovered with good spatial relationships and are reported here as "Rt preOp" and "Lt preOp" (the third sample, collected from the purge duct, was damaged during sampling). These samples were collected from the right and left blanket above the purge duct before any payload bay operations had been initiated. The next set of three lifts at Edwards were collected after the payload bay operations had been performed and were collected in exactly the same locations as the original lifts. The last three were collected from different locations as pre-ferry flight references. The sample labeled "Rt PreFerry1" was collected from the right blanket near the adapter plate. The other sample from the right side, "Rt PreFerry2", was collected from the lower center of the square one over from the PSA. The final lift from Edwards is plotted on the OPF chart and is labeled "Lt PreFerry". It was collected from the left

side blanket near the optical target. These samples all fell between log/log squared curves with a slope of 0.38 for level 5000 and level 10,000. Using a slope of 0.93 from MIL STD 1246B they met the Level 1000 requirements for particles 100 micrometers in greatest dimension or smaller, and those of a Level 2000 at 500 micrometers or smaller.

The samples with the highest counts for this set were those collected just before the ferry flight. These samples are consistent with the eyewitness account regarding the visible airborne particulate matter in the Shuttle Bay during sampling. The first two lifts collected tended to have fewer large particles than the lifts from the same location taken later. This testifies to the constant redistribution of particles within the Shuttle Bay while the purge system was in operation and the Shuttle was being moved. Thin aluminum flakes, the residue of vapor deposited aluminum on Kapton after the Kapton had been removed by atomic oxygen, was the most obvious "snow" in the Shuttle Bay but the tapelift samples indicated they were not the only particles being redistributed. The three samples collected in the OPF are essentially identical in location to the preferry flight samples and again indicate the continued redistribution of contaminants. The redistribution of particles in the Shuttle Bay seems to be associated with turbulence in the bay. Low velocity flow created sufficient turbulence to circulate the vapor deposited aluminum flakes. Higher velocities were required to redistribute smaller particles and particles with lower effective Reynold's numbers. The effects of higher velocity airflow erosion of surfaces has been seen in a number of areas on LDEF and one such case is documented in Reference 1, photograph 15. All samples from the Shuttle Bay indicate the same basic types of particles and similar particle populations. The particles in the original tapelifts contained considerable amounts of small vapor deposited aluminum flakes and angular fragments of etched Kapton. Small yellow spherical ash particles of Kapton were also seen associated with the vapor deposited aluminum particles and as separate particles. Minerals were common and were identified as calcite (calcium carbonate), chalcedony (silicon dioxide), emery (aluminum oxide), and a variety of silicates. Some of these may have been industrial abrasive residues. A variety of glass fibers were found. Glass fiber from the Shuttle tile and from the bay liner were identified but filter fiber, insulative fiber, and glass from composite materials was also seen though specific sources have not been identified. Sequential lifts from the same locations indicated the redistribution of particles with a tendency for a gradual increase in population with time as the surfaces of LDEF continued to degrade. More fragments of aluminum flake and of the brown molecular film from LDEF were seen in the later lifts as well as more minerals and industrial residues not associated with LDEF as a source. These trends continued from the second set of lifts at Edwards through the set at Kennedy in the OPF.

The next set of samples were collected from the Transportation Canister used to transport LDEF from the OPF to the O&C building. The control sample count was a bit high but was still an order of magnitude less than the sample counts. This high particle count on the control is generally indicative of a non-laminar flow controlled environment and is the result of the static charge on the tape when it is first pulled from the roll collecting particles before the tape is sealed on the microscope slide. The surface cleanliness of the canister met a Level 1000 for particles less than 250 micrometers. The curves were consistent with a level 5000 when a slope of 0.38 was used. Most of these particles were from LDEF materials though pine pollen was first evident in these samples. After moving to the O&C the surfaces were over an order of magnitude higher in particle count. Most of these additional particles were from LDEF. These samples were all collected from the floor of the canister, to the side and below LDEF.

LDEF was placed on the LATS in the O&C building. Tapelifts were taken from the LATS after LDEF was in place and then again after the transport to SAEF-2. Large numbers of pollen grains, cellulose fibers, and other non-LDEF particles were seen in the first samples though degraded LDEF materials still were the majority of the population. Once in SAEF-2 the LATS was periodically cleaned. The LATS tapelift particle population in SAEF-2 reflects 'recent' depositions plus the background to which the LATS was cleaned. Initially most of the particulate was from LDEF though many other sources were well represented. By March particulate contaminants from SAEF-2 sources began exceeding those from LDEF sources on the LATS. This included paper fiber, worn flooring material, natural minerals, pollen and plant parts, skin, clothing fiber, hair, sawdust, and other materials. The tapelift samples from other areas in SAEF-2 always tended to be from sources other than LDEF.

By April 14, 1990 all trays had been removed and a detailed survey had been made of the surface of the LDEF structure by the Meteorite and Debris Special Investigation Group. At that time the Materials Special Investigation Group was given access to LDEF to collect tapelift samples directly from the LDEF structure. All of these samples were collected from the anodized aluminum exterior surface. Samples were collected from surfaces that were covered by tray clamps and adjacent areas that had always been exposed. A detailed analysis of these samples has not been completed though some of them have been analyzed for the particle size distribution. The distribution curves were a bit steeper than 0.38 but were around a level 5000 of that slope. All but one sample fell below a MIL STD Level 1000 for particles smaller than 250 micrometers.

The average fallout counts reported in Figure 4 would seem to indicate a relatively clean environment in SAEF-2 as would the airborne particle counts of Figure 7. The results for particles per square foot per twenty-four hours from the fallout monitoring technique appear to be about an order of magnitude lower than would be expected based on those seen on actual surfaces. The particle population by size distribution curve indicated by the fallout monitoring technique suggested a semilog plot (log population by linear diameter). This indicates a disproportionately low number of larger particles compared to a log/log or log/log squared distribution. Tapelift results and the direct inspection of LDEF surfaces did not support the suggestion of a scarcity of large particles in the SAEF-2 environment. The relative absence of large particles from the fallout monitoring technique used may be a statistical effect of the small area sampled.

### Results of the Quantification of Molecular Films

The presence of molecular films on the surface of LDEF was easily detected by the characteristic brown discoloration of many surfaces. Reference 3 at the end of this paper is an article on LDEF molecular contaminants and discusses the detection and qualitative analysis of these films. The discoloration of surfaces is evident at thicknesses less than those required to produce the first interference color fringe. The brown layer on the FEP Teflon of tray C-08 is clearly visible before the first red/brown interference fringe. That first fringe corresponds to a film thickness of approximately 0.1 micrometers (see Figure 8). The distribution of films on the surface was very complex with vent area deposits often tens of micrometers to hundreds of micrometers thick, large area deposits on the backs or sides of trays on the order of micrometers thick, and exterior surfaces with deposits of tens to hundreds of nanometers. There were also surfaces with no detectable deposited films. These were typically surfaces that were outgassing non-condensing materials, such as water, or that were chemically attacked and eroded by atomic oxygen. Numerous individual measurements of film thickness and area of coverage were made for specific trays. A first approximation of the total volume of the molecular films on LDEF was made by extrapolating data from selected trays to the entire surface of LDEF. The molecular film volume data for these trays projected onto the face area of the trays (34 by 50 inches) averaged a little under one micrometer in thickness, but this did not include the thick deposits found on the earth and space ends of LDEF. The projected surface of LDEF had a combined surface area (inside plus outside surface) of approximately 304 square meters. A thickness of one micrometer was assumed for the film spread out over the entire surface of LDEF with a density of 1.68 as measured on fragments of the thicker films. Multiplying the surface area by the film thickness and density results in a value of 511 grams of material. Considering the nature of this estimate this value can be represented as approximately one pound.

The interior of LDEF was coated with over 260 square meters of black urethane paint (Z306) at a thickness of approximately sixty micrometers and a primer coating of approximately twenty micrometers for a total volume of 0.026 cubic meters or 26,000 cubic centimeters. With a density of about 1.5 grams per cubic centimeter this amounts to 39,000 grams of paint. Test coupons with this same configuration of primer and Z306 were tested using the standard Volatile/Condensable Materials (VCM) test procedure. The painted surface was heated to 125 degrees Celsius and the collector surface was at 25 degree Celsius.

These conditions were maintained for nearly forty-eight hours. The painted surface lost 2.4 percent of its weight and the collector surface collected 0.4% of the weight of the original paint film. This would amount to 975 grams of volatile material from the Z306 covered surfaces alone, of which 156 grams would condense on surfaces at 25 degrees Celsius. Temperatures on LDEF were often significantly lower than 25 degrees Celsius. Tests to determine the amount of silicones present on LDEF indicate about 6,000 grams on experiment A0178 and at least that much more on other experiments for a total of over 12,000 grams. None of these materials had been baked out so the weight loss in orbit may have been near 5%. This corresponds to 600 grams of volatile material. If these two materials are assumed to contribute half of all of the outgassing products from LDEF then the molecular film on the interior and exterior surfaces of LDEF constitute approximately 10 to 15% of the outgassed materials available.

During the preliminary examination of LDEF shortly after it arrived at SAEF-2 a number of areas were found that indicated the presence of non-volatile hydrocarbons or silicones prior to orbital exposure as mentioned earlier in this paper. Subsequent analyses in the laboratory of the back surfaces of clamps and shims indicated that some of them contained residual hydrocarbons, silicones, or combinations of the two that were thick enough to generate suitable infrared spectra directly from their surface even after nearly six years in orbit. Such spectra required a pathlength on the order of a micrometer thick (see Figure 8). Considering the area of coverage for some of the thicker deposits and that the areas providing no suitable spectra also contained some background level of non-volatile residue an average film thickness of about 0.025 micrometers would seem to be a reasonable estimate. This value, assuming a density for the film of one gram per cubic centimeter, would equate to a MIL STD 1246B NVR Level C. This amount of NVR would account for a total weight of about 25 grams if it had all been converted to brown film and been fixed in place. This is an order of magnitude less than the estimated weight of the film deposited on the surface of LDEF while in orbit.

### CONCLUSION

Based on the results of the analyses completed to date and first approximation values for outgassing materials and films the following conclusions can be presented:

In discussing the cleanliness levels of LDEF surfaces slopes other than the standard MIL STD 1246B slope of 0.93 are more useful. Slopes between 0.4 and 0.6 seem to be most useful.

Using a modified slope of approximately 0.4 the surface of LDEF corresponds to approximately a level 5000. This corresponds to a MIL STD 1246B Level 1000 or less for particles smaller than 250 micrometers and a Level 500 for particles smaller than 50 micrometers.

The number of particles on some LDEF surfaces increased by nearly an order of magnitude from orbital values to those measured after removal from SAEF-2.

For many surfaces of LDEF the particle count remained reasonably constant though the types of particles and their sources changed.

Redistribution of particles during purging operations and the ferry flight was indicated by repeated tapelift analysis of the same locations before and after these operations.

The deposited molecular films amounted to approximately one pound of material.

Materials intentionally used on LDEF accounted for nearly all of the contaminating film found after recovery of the satellite. Based on outgassing estimates the molecular films on LDEF represent 10 to 15% of the outgassed materials available.

Non-volatile residues (NVR) present as contaminants on the surface of LDEF at launch are estimated at about 2.5 milligrams per square foot of surface, MIL STD 1246B Level C. This would account for less than 10% of the total deposited contaminating film found on LDEF after recovery from orbit.

### REFERENCES

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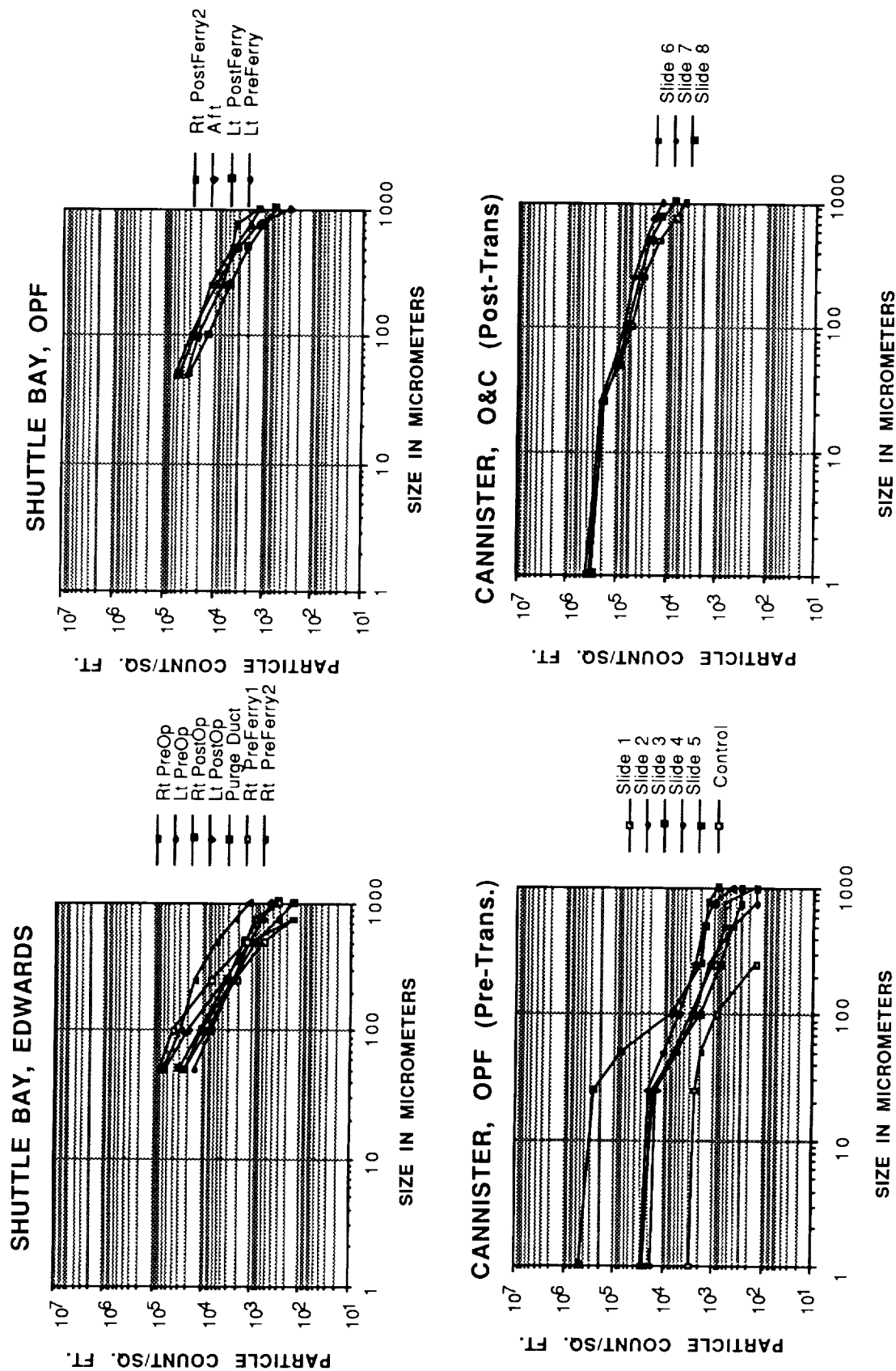


Figure 1: Tapelift data from the shuttle bay at Edwards and the OPF and from the canister at OPF and the O&C.



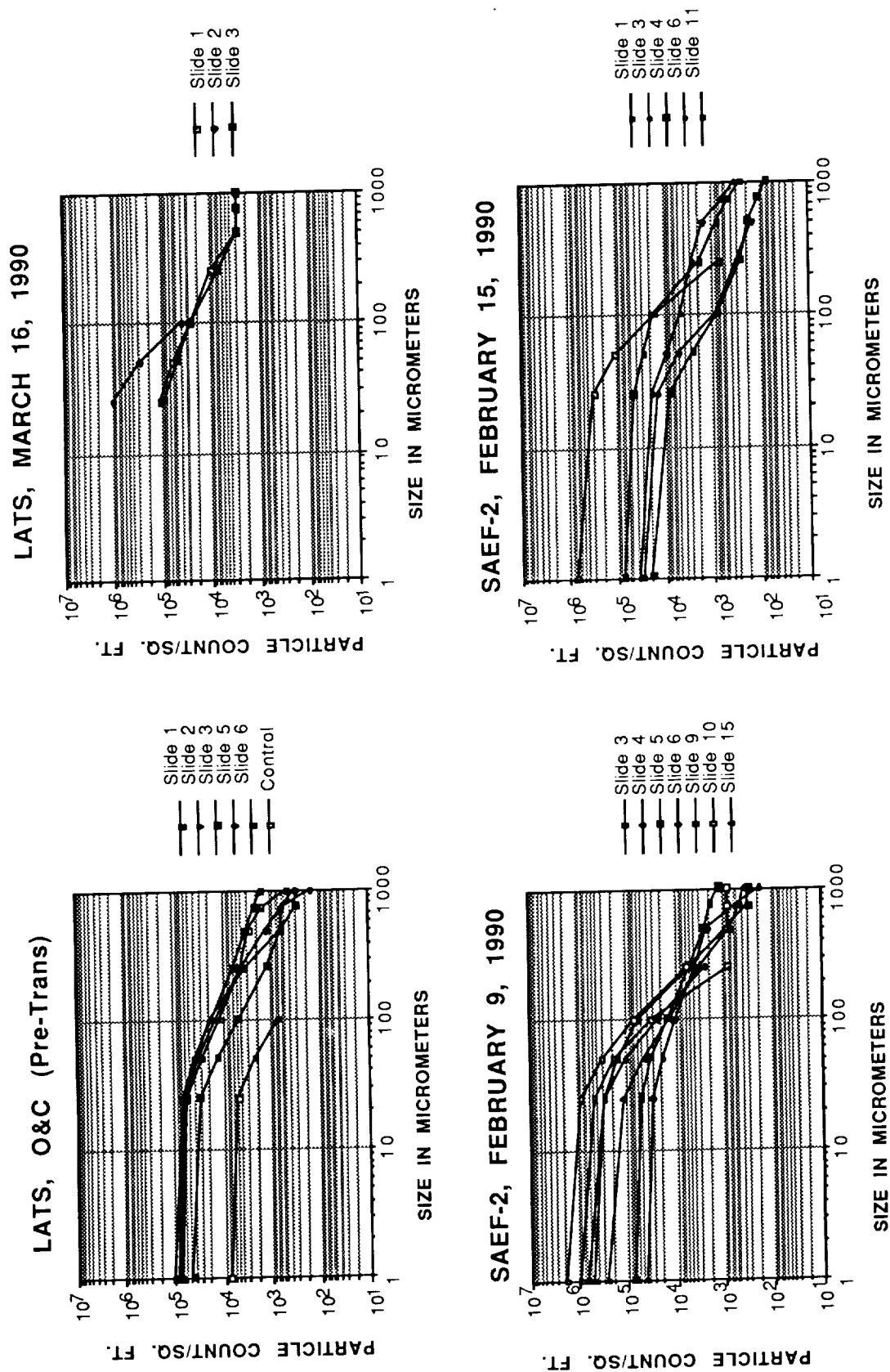


Figure 2: Tapelift data from the LATS at O&C and SAEF-2 on March 16, 1990 and SAEF-2 from February 9th and 15th, 1990.

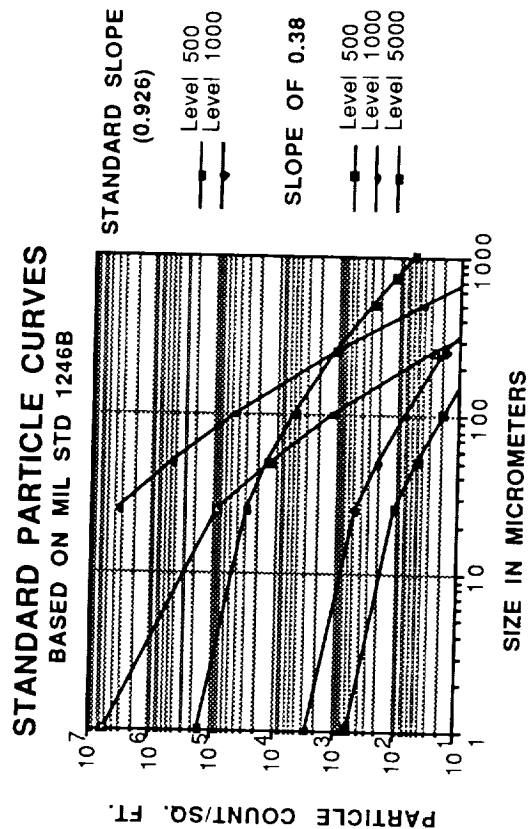
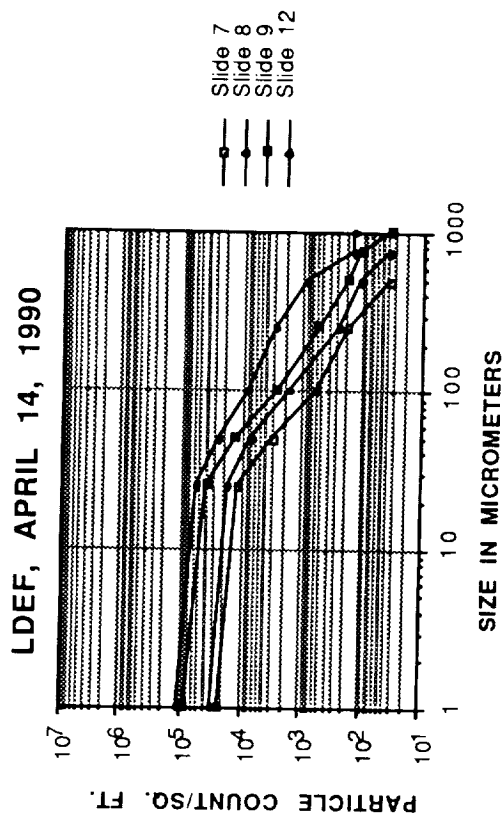


Figure 3: Tapelift data from the surface of LDEF collected on April 14th, 1990 and standard particle distribution curves.

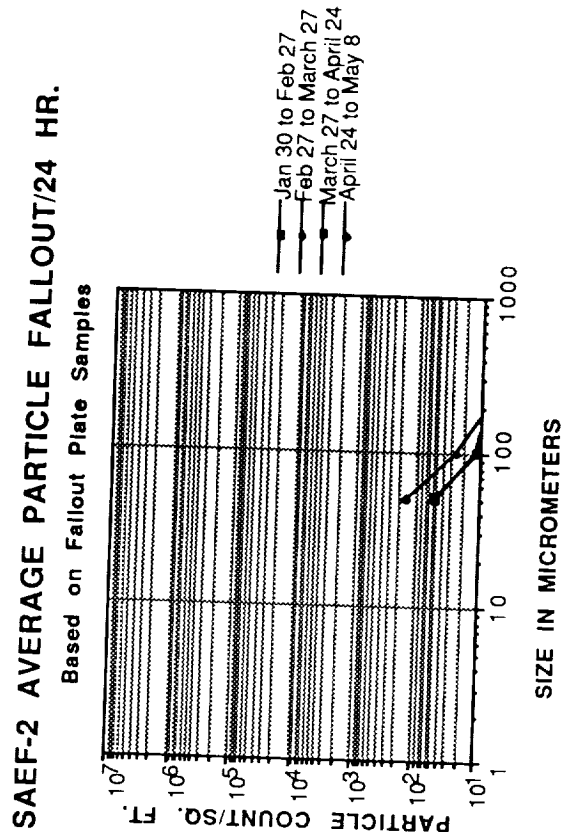
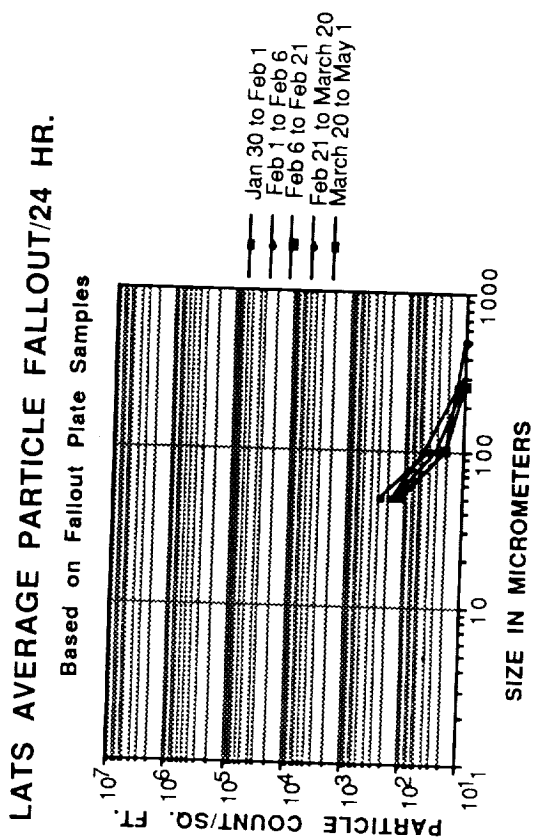


Figure 4: Data provided by NASA based on particle fallout test plates used to monitor SAEF-2 and the LATS.

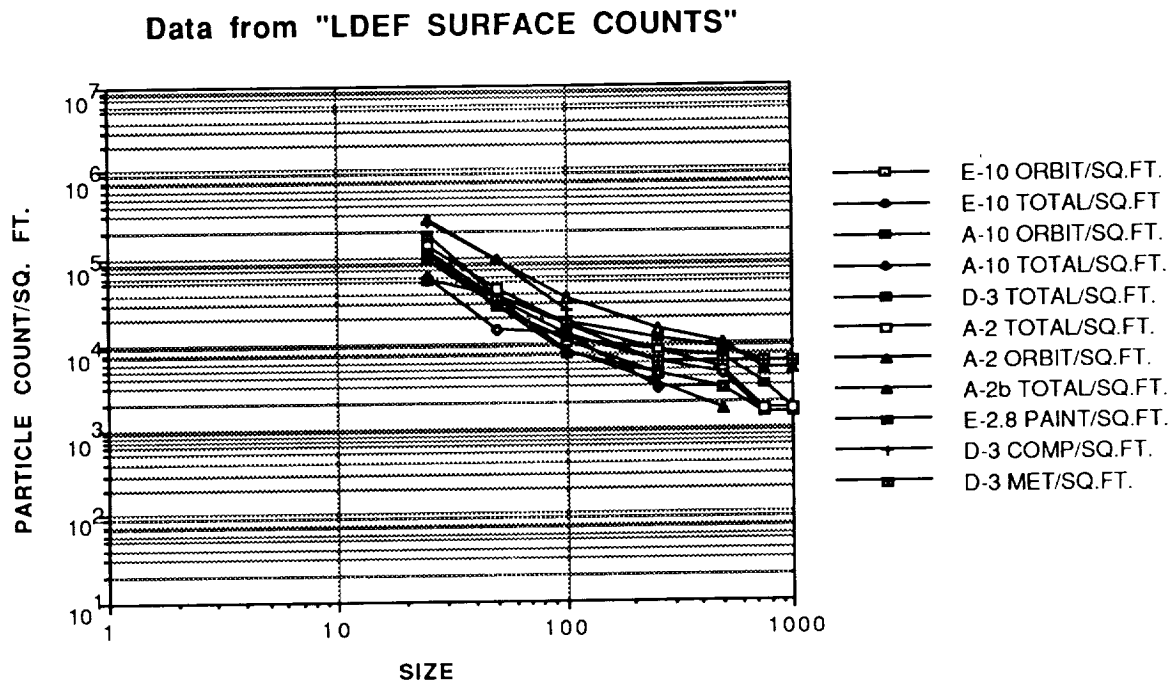


Figure 5: Particle counts directly from LDEF surfaces; total counts and counts for particles present in orbit.

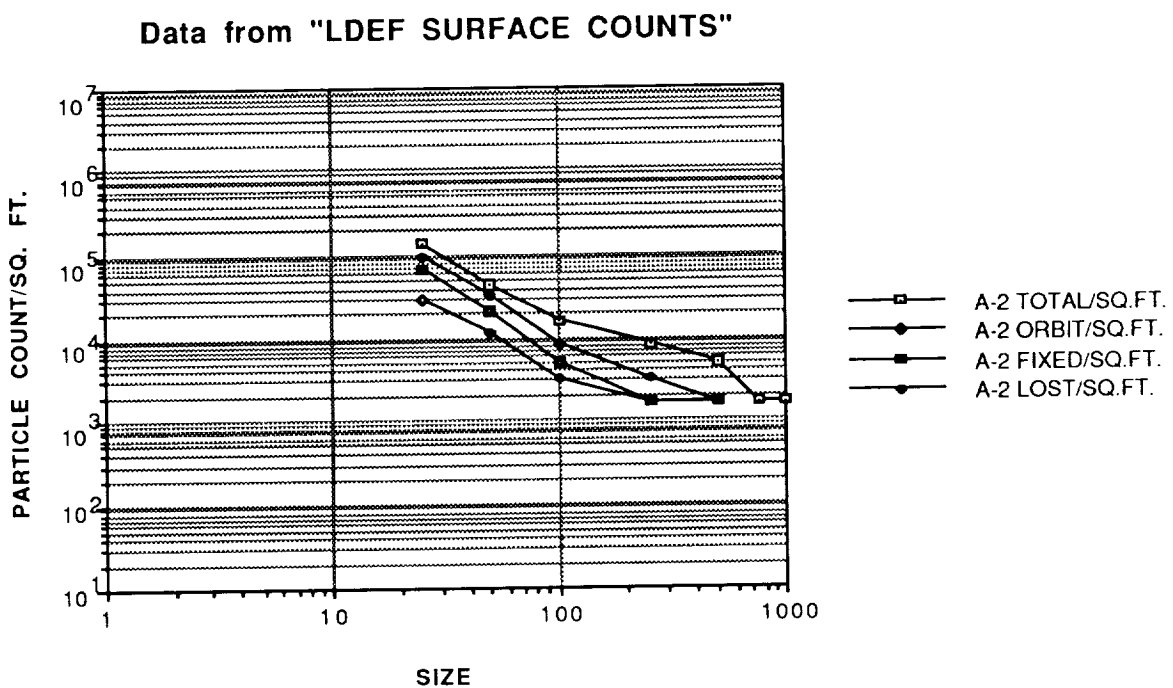
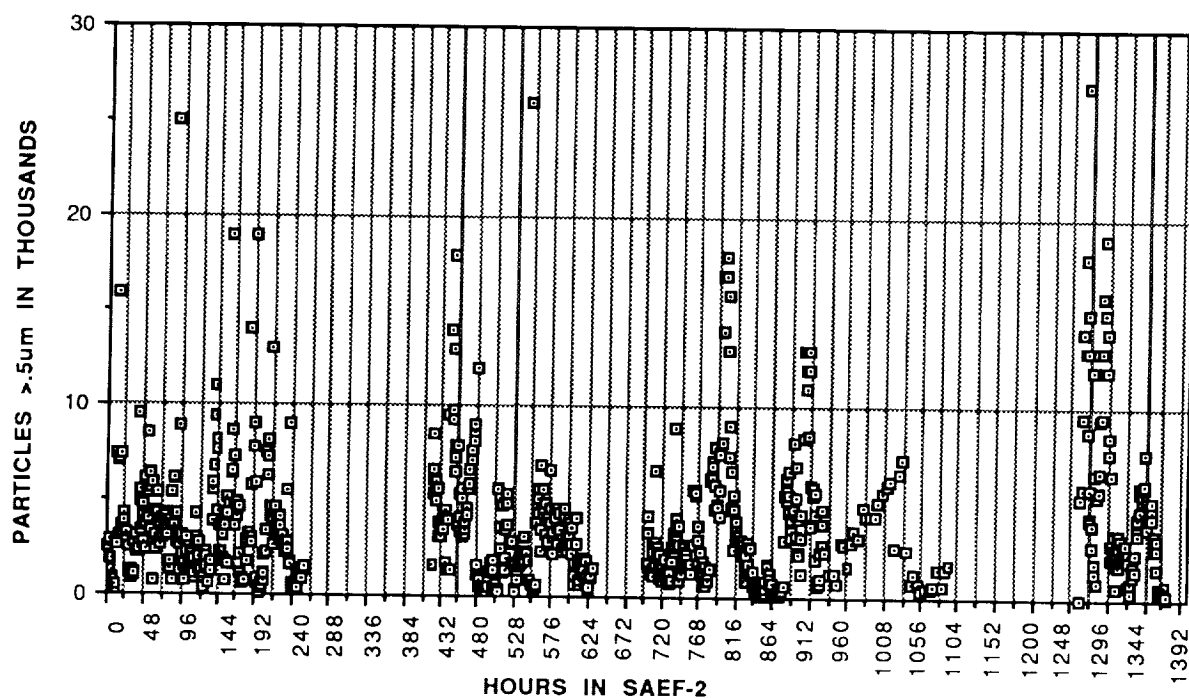


Figure 6: Detailed count of particles near the edge of tray A-02 by particle history; the total number of particles present at the time of analysis, the number of particles present while in orbit, the number of particles present in orbit that moved during recovery, and the number present in orbit that were still present following recovery and SAEF-2 exposure.

# **HOURLY PARTICLE COUNTS IN SAEF-2 HI-BAY FROM LDEF ARRIVAL TO LAST TRAY REMOVAL**



# **HOURLY PARTICLE COUNTS IN SAEF-2 AIRLOCK FROM LDEF ARRIVAL TO LAST TRAY REMOVAL**

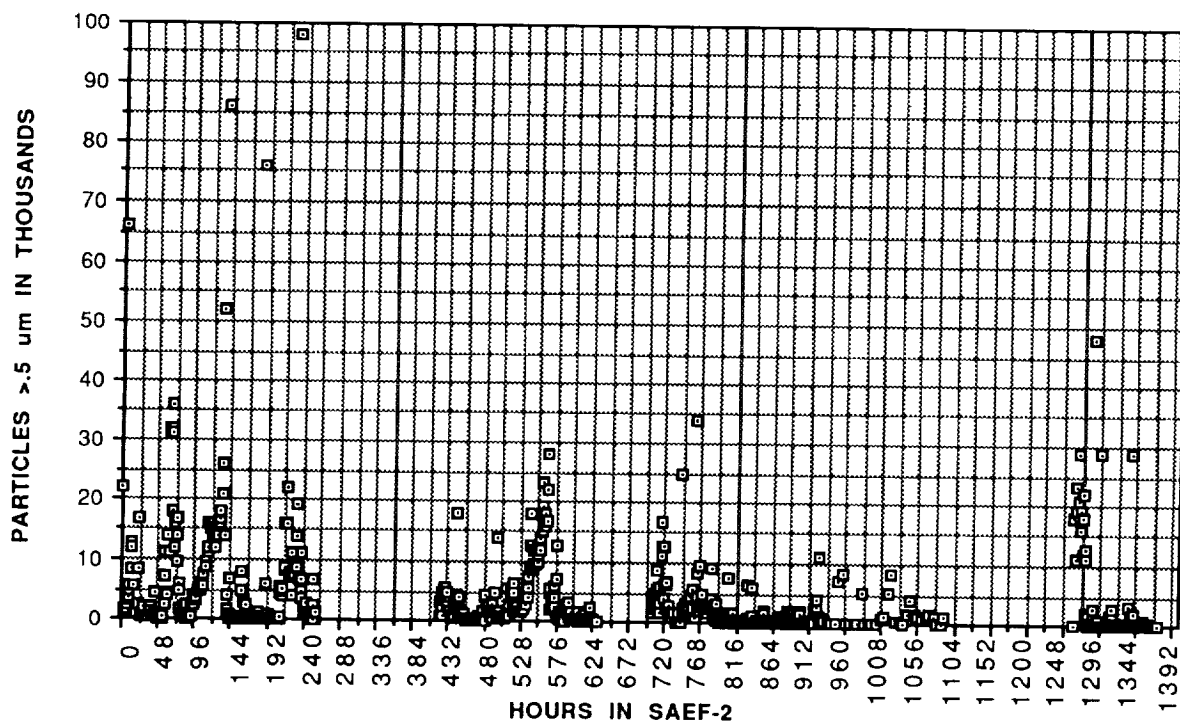
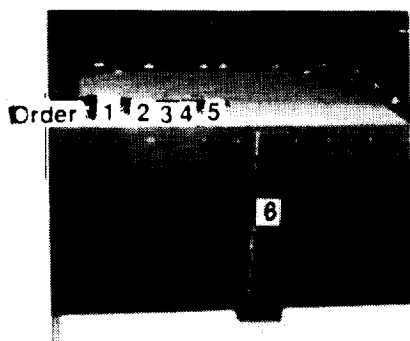
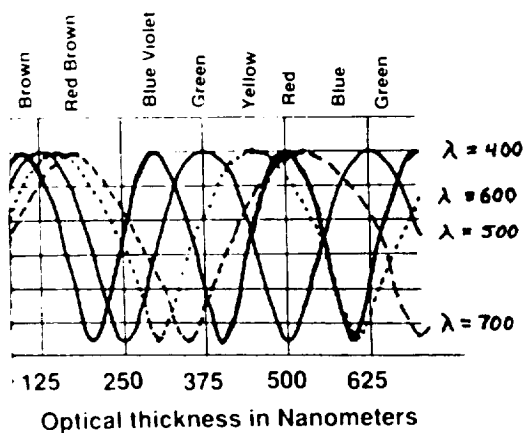


Figure 7: Hourly automatic airborne particle counts for the SAEF-2 airlock and highbay from LDEF arrival to the removal of the last experiment tray.



Interference Film  
Colors on Tray F-06

Thickness as a Function  
of Interference Color



Diffuse Reflectance IR  
Spectral Response  
by Thickness

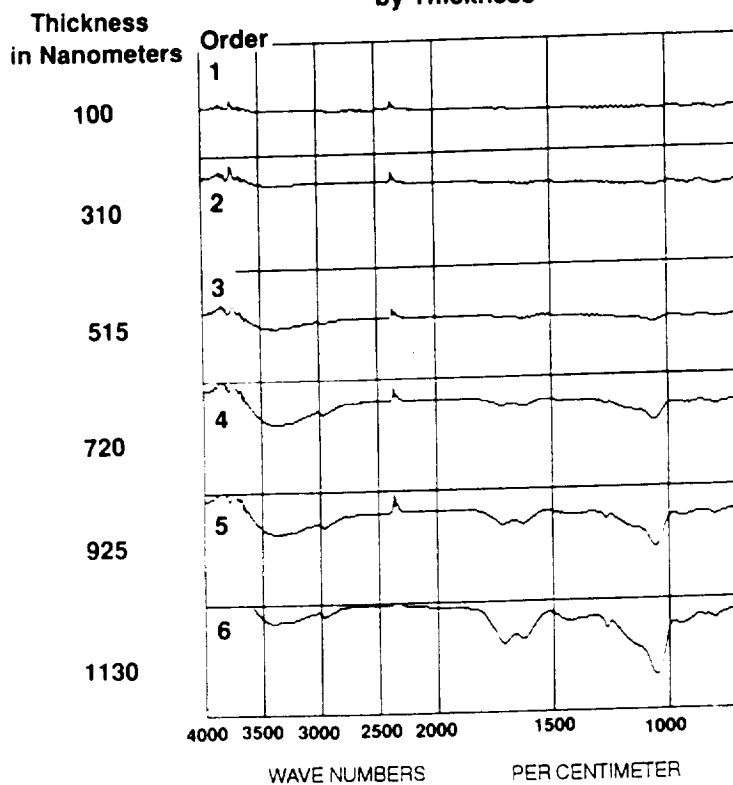
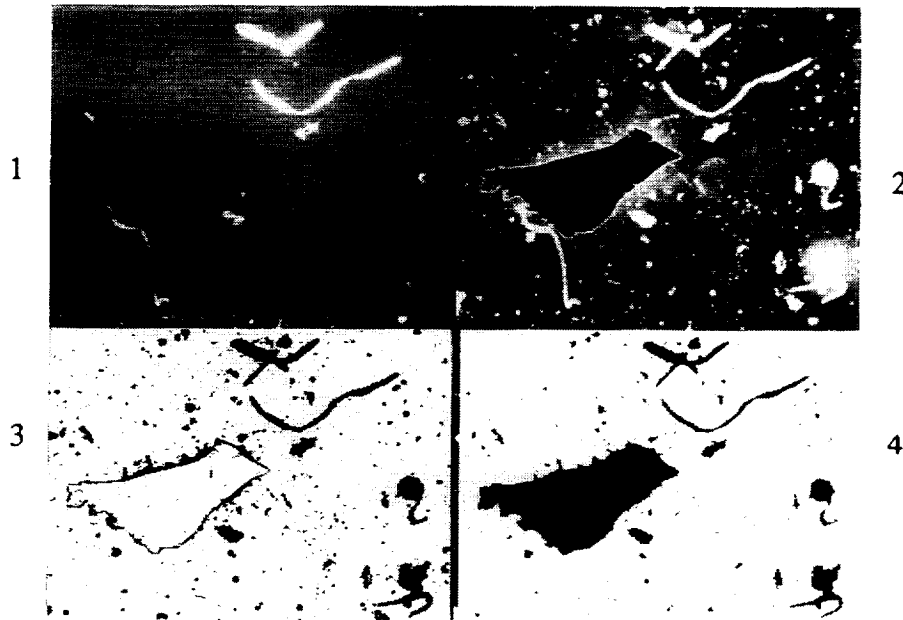


Figure 8: Quantification of molecular films by interference color and the calculation of the total film weight.

(See color photograph, p. 597.)

ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH



Photograph 1: Processing of the image for automated image analysis particle counts  
 Frame 1: Transmitted brightfield, off crossed polarizing filter illumination.  
 Frame 2: Darkfield illumination image.  
 Frame 3: Computer detected darkfield image.  
 Frame 4: Final field with particles imaged as analyzed.



Photograph 2: Interference colors indicating the thickness of the brown film on tray H-06.

(See color photograph, p. 598.)



Photograph 3: Fingerprint residue, tray B-04, clamp 2.